Building a Geomechanical Framework for Interpreting DAS Measurements

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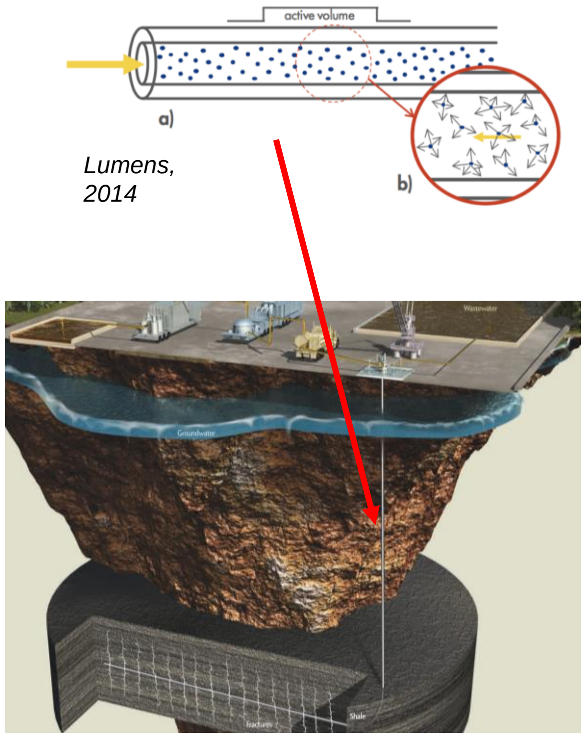
Introduction to Fiber Optic Distributed Acoustic Sensors (DAS)

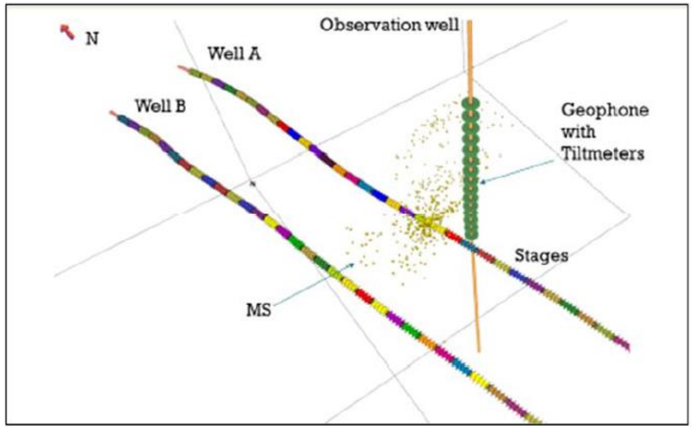
- DAS is designed to measure signals at a high spatial resolution (~ 1 m) over large distances (multiple km)
- DAS uses the fiber itself as a sensor to measure strain (or strain rate) along its length
- Its development has opened up a massive source of data for subsurface characterization / monitoring
- Questions:
  - How can we optimize the performance of DAS?
  - How do we interpret the data we collect?

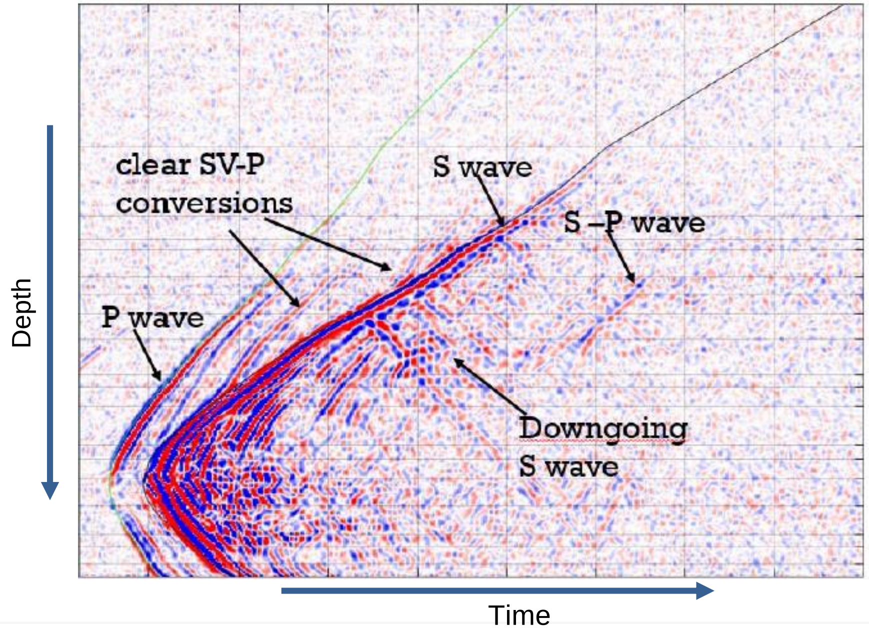


Lumens, 2014

DAS Examples – Microseismicity

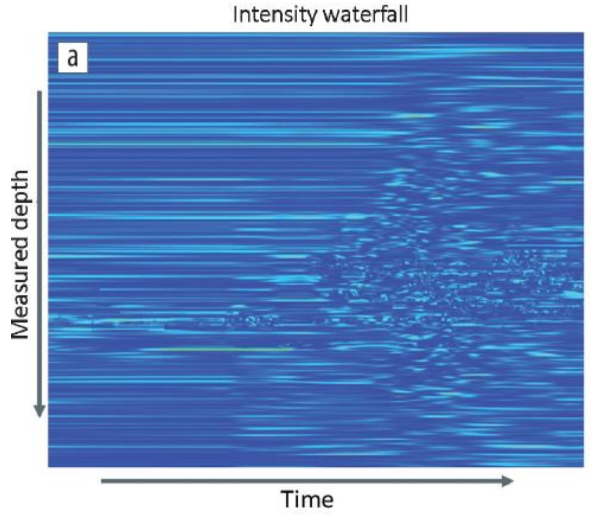
- Comparison of traditional geophone and DAS monitoring programs (Hull et al., 2017)
  - Sensors located in an offset vertical well, with hydraulic stimulations in a nearby horizontal well
  - DAS config: L = 760 m, L_{gauge} = 10 m, F_s = 2 kHz
  - Geophone config not specified (lower resolution)
  - Microseismic events recorded during an example stage
    - DAS = 31 events (minimum M_w = -2)
    - Geophones = 785 events (minimum M_w = -2.68)
    - Note: different event detection algorithms used



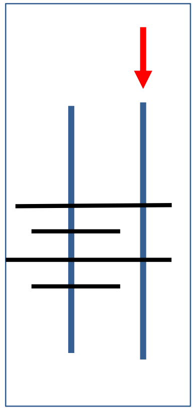


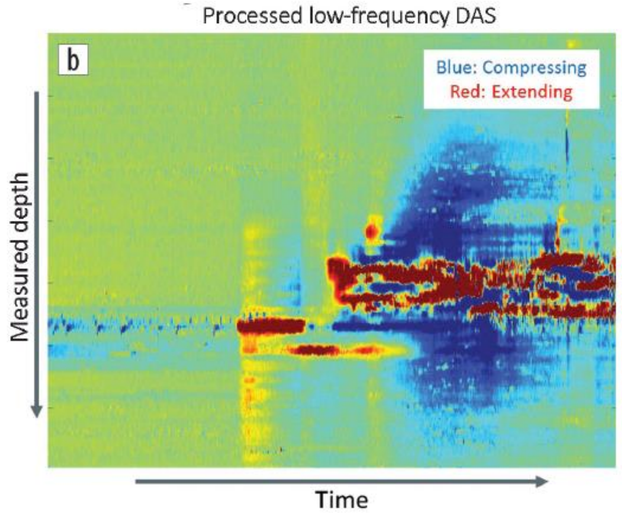
DAS Examples – Waterfall Plots and Low-Frequency Strain

- Hydraulic fracture geometry characterization attempts (Jin and Roy, 2017)
  - Fracture stimulation and DAS in adjacent horizontal wells
  - DAS configuration: L_{sample} = 1 m, L_{gauge} = 5m, F_s = 10 kHz
- Waterfall plots
  - Vibrational energy for a given frequency band
  - Excited by the opening and fluid flow in fractures?
  - Tend to be messy and difficult to interpret
- Low-frequency strain measurements
  - Carefully filter the data to estimate near-DC component of strain rate (this example: f < 0.05 Hz)
  - Matches the psuedostatic fracturing process



Plan View



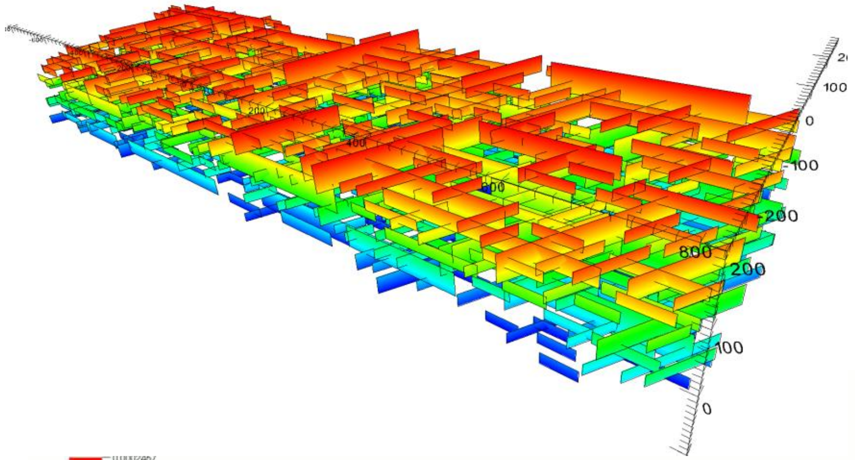


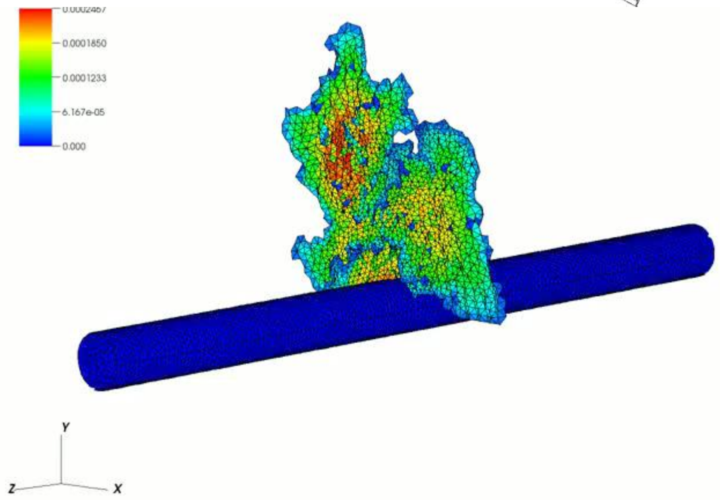
Large-Scale Geomechanical Modeling

- Goal: Develop a framework for interpreting DAS measurements that is robust, quantitative, and grounded in geomechanics

- Due to its topicality, focus our initial efforts on hydraulic fracture monitoring

- Implement a model of DAS in GEOS (LLNL)
  - HF modeling from near-wellbore to reservoir scales
  - Geothermal energy production
  - Microseismicity
  - Etc.





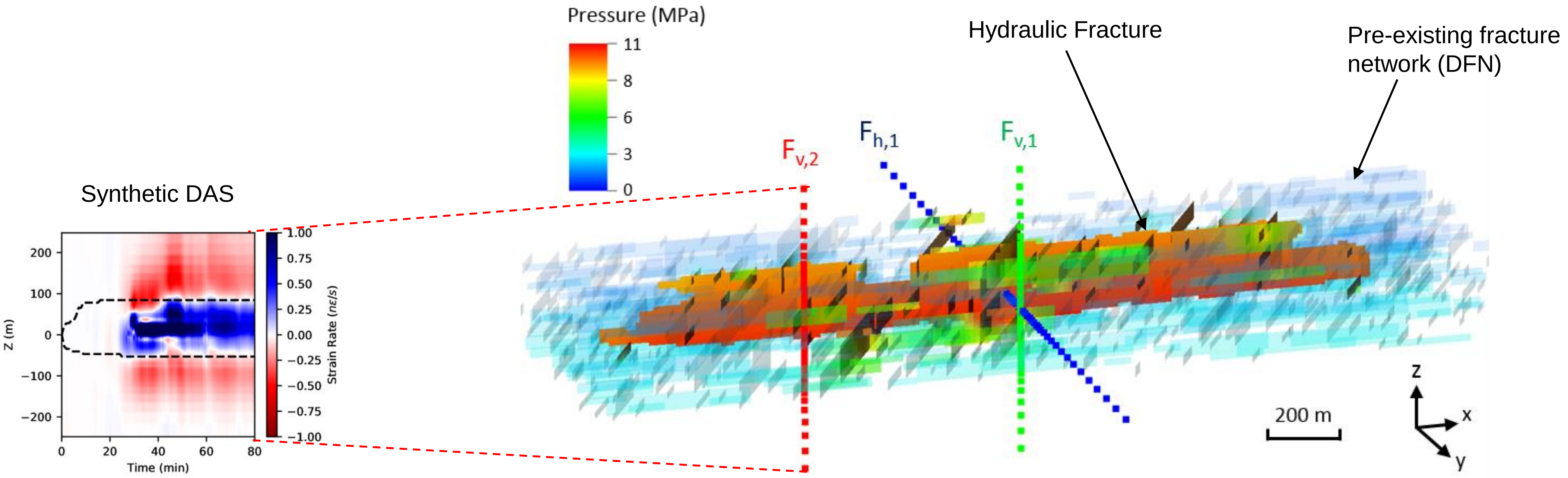
GEOS Fiber Modeling

- Fiber model:
  - The scales of interest are way too large to explicitly mesh the fiber
    - Instead, define a virtual fiber as a set of nodes in the underlying FE mesh
    - Assume that the fiber is perfectly coupled to the rock and is insensitive to shear
  - Record the nodal displacement along the virtual fibers at high frequency
  - Use central-difference operators to calculate strain and/or strain-rate
  - Apply an arbitrary gage length applied via a convolutional filter during post-processing

- The target DAS signals are often very small (~1 nε/s)
  - Challenging constraint for large heterogeneous models, explicit discontinuities
  - We use a combination of implicit/explicit time-stepping to bring the model into an initial equilibrium state
  - Before loading, we track the drift/noise in the model and require a S/N of at least 10

GEOS Fiber Modeling

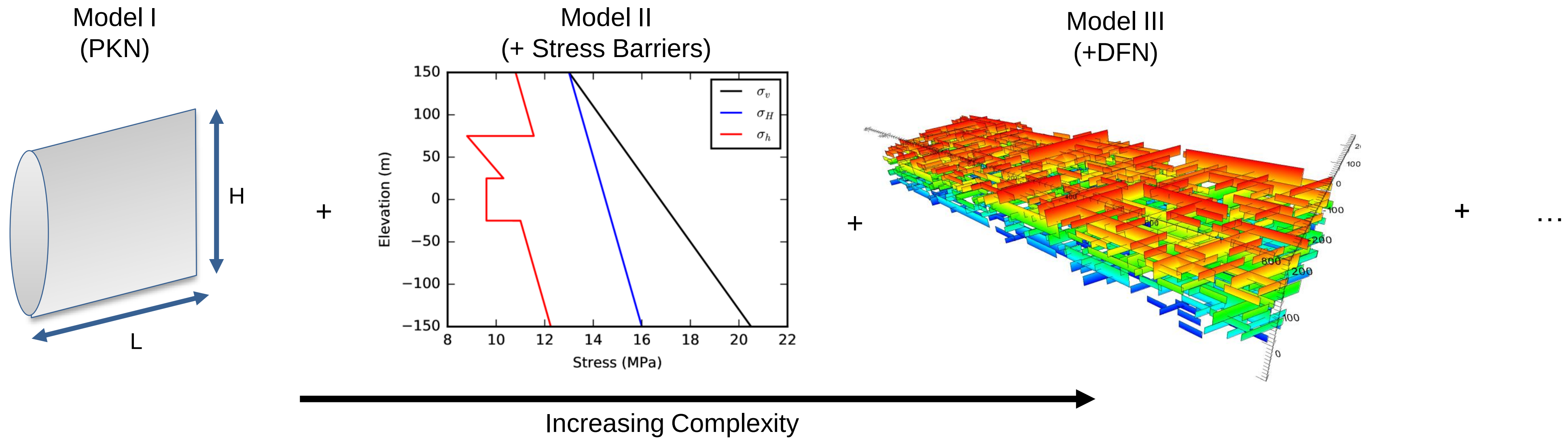
- Instead of looking at a particular case study, focus on a set of idealized models
  - Geologic model sensitivity
  - Stimulation design sensitivity
  - Target low-frequency DAS on three fibers (f << 1 Hz)



Geological Model Sensitivity - Design

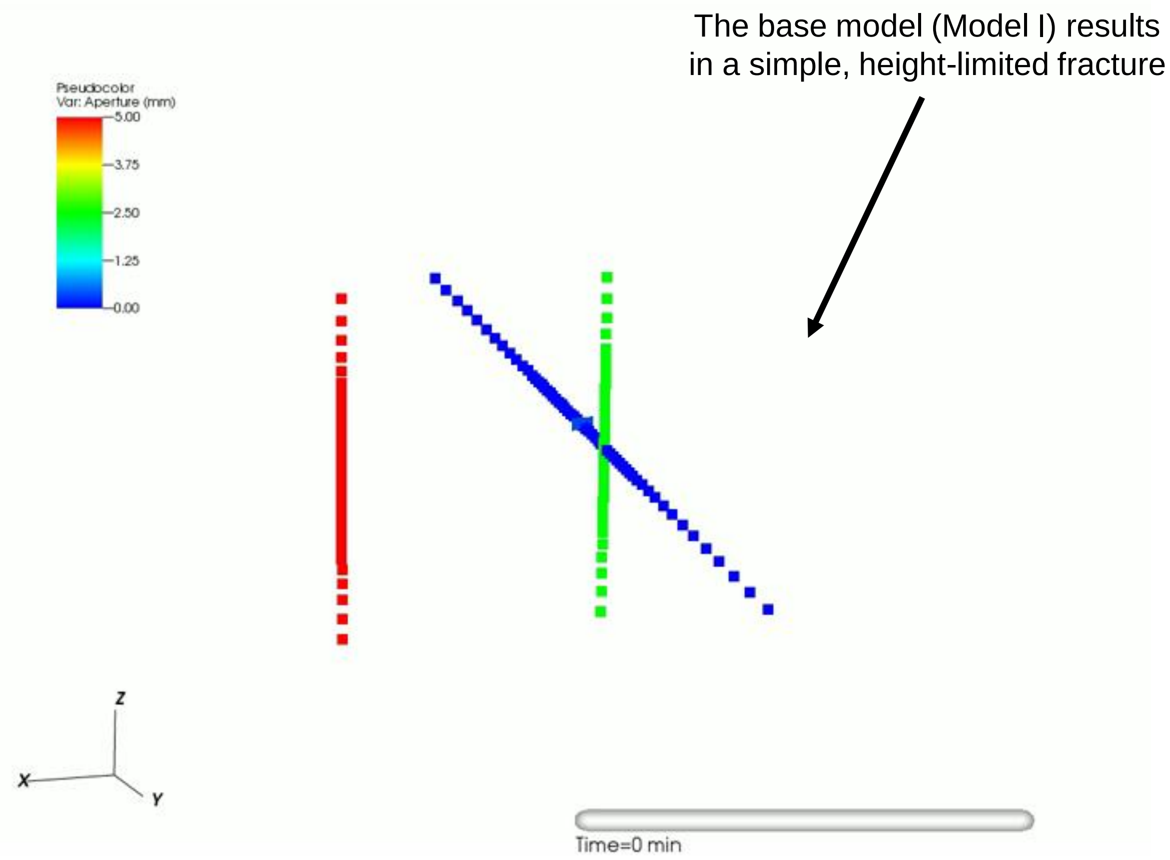
- Base model:
  - 50 m tall PKN fracture propagating from a horizontal wellbore
  - In-situ stress state is normal
  - Fluid injected into a single perforation cluster for 80 minutes at 0.05 m^3/s

- Increase the complexity of the model to isolate signals of interest in the DAS

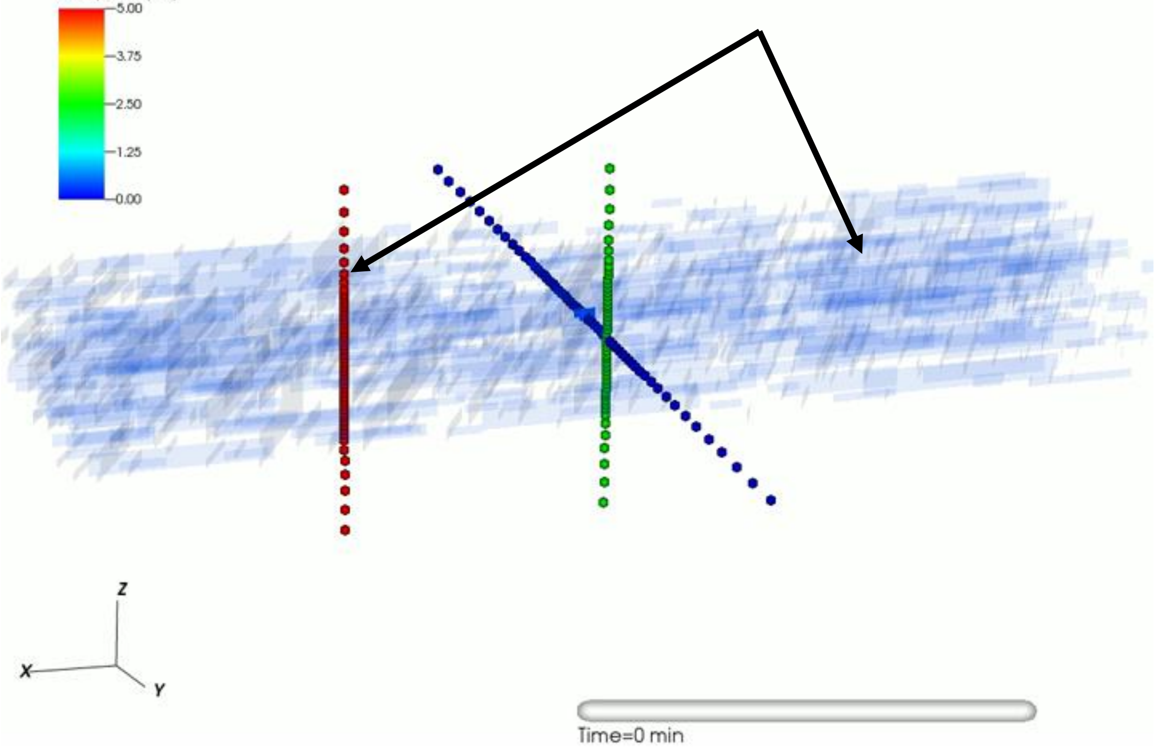


Geological Model Sensitivity – HF Generation Examples

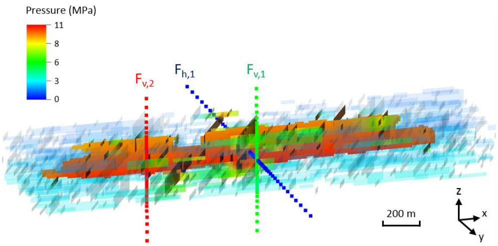
The base model (Model I) results in a simple, height-limited fracture



The addition of the stress barriers (Model II) and DFN (Model III) introduces significant complexity into the generated fracture



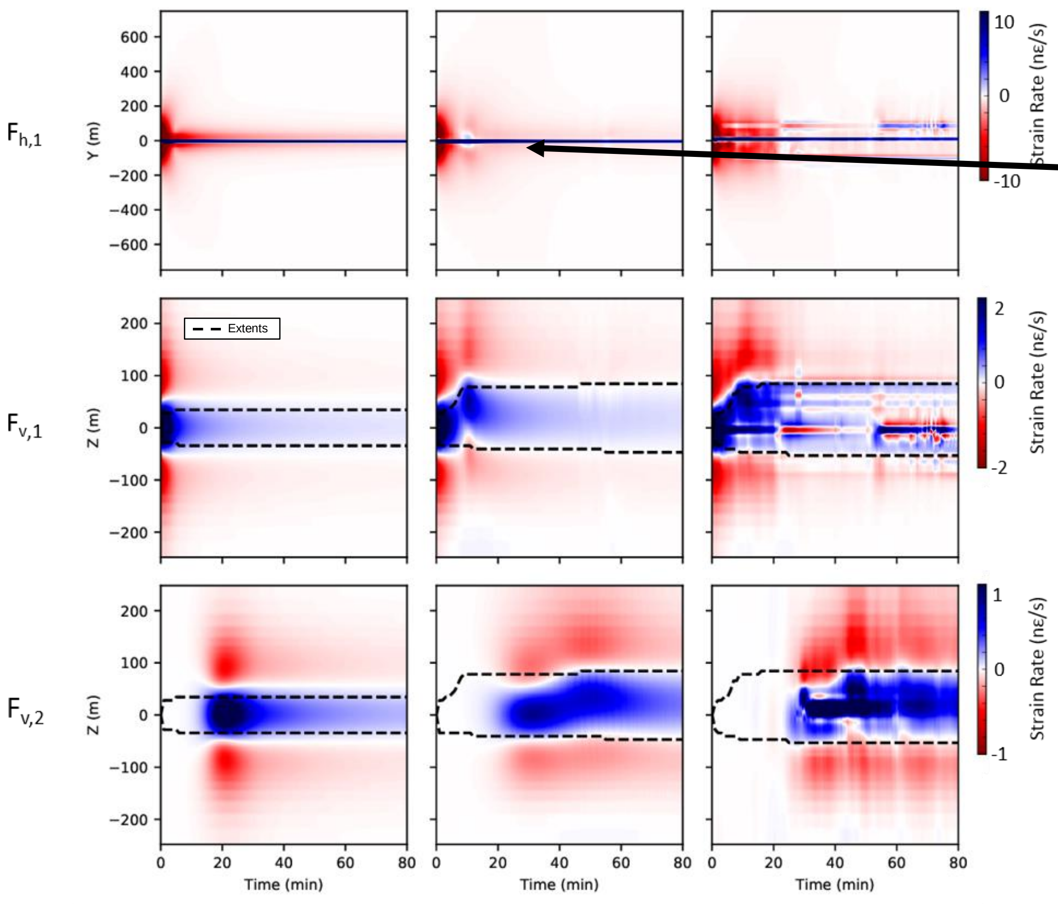
Geological Model Sensitivity – DAS Results



Horizontal Well

Vertical Offset Well (x = 0 m)

Vertical Offset Well (x = 380 m)

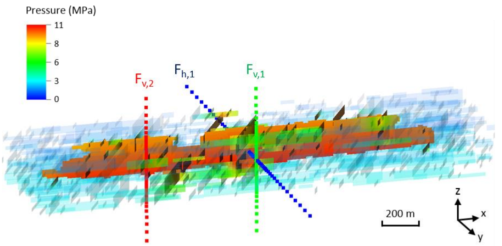


The measured strain rate in the horizontal well is dominated by the opening of the perforation

Model I	Model II	Model III
Base Model	+ Stress Barriers	+ DFN

Extension Compression

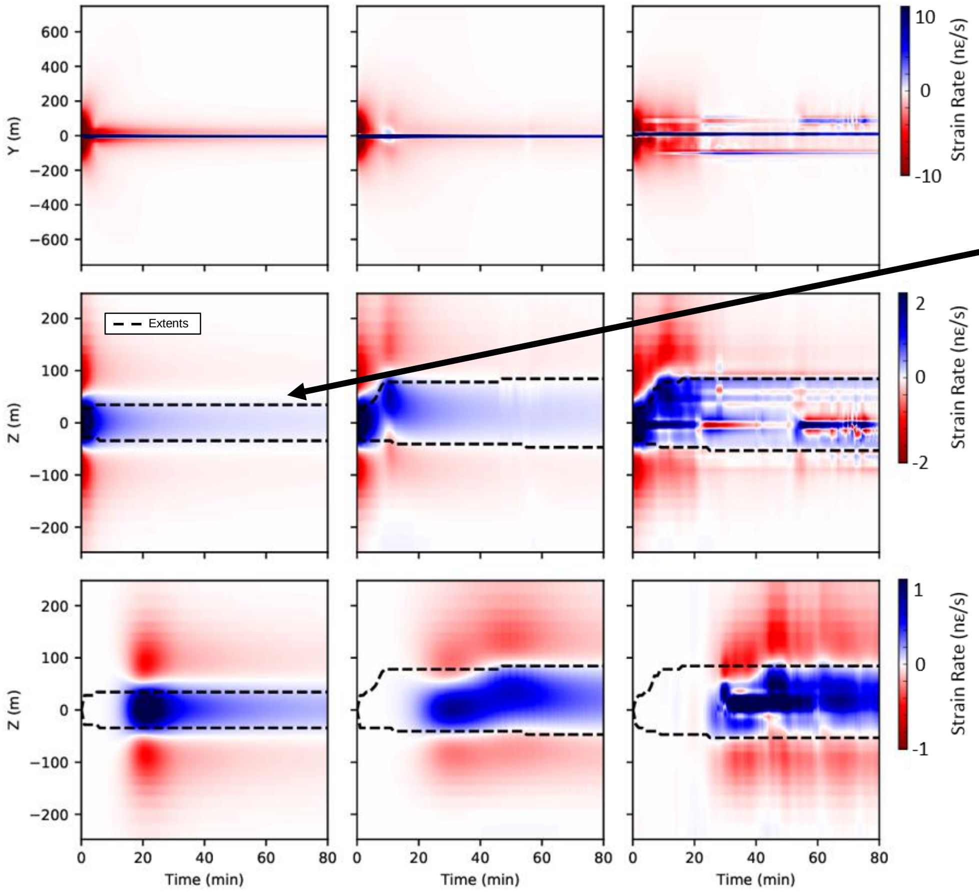
Geological Model Sensitivity – DAS Results



Horizontal Well $F_{h,1}$

Vertical Offset Well (x = 0 m) $F_{v,1}$

Vertical Offset Well (x = 380 m) $F_{v,2}$



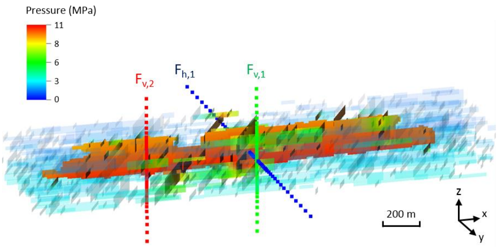
Model I | Model II | Model III

Base Model | + Stress Barriers | + DFN

The measured strain rate in the vertical wells displays this characteristic Ricker-like pattern along the length of the fiber

Extension Compression

Geological Model Sensitivity – DAS Results



Horizontal Well

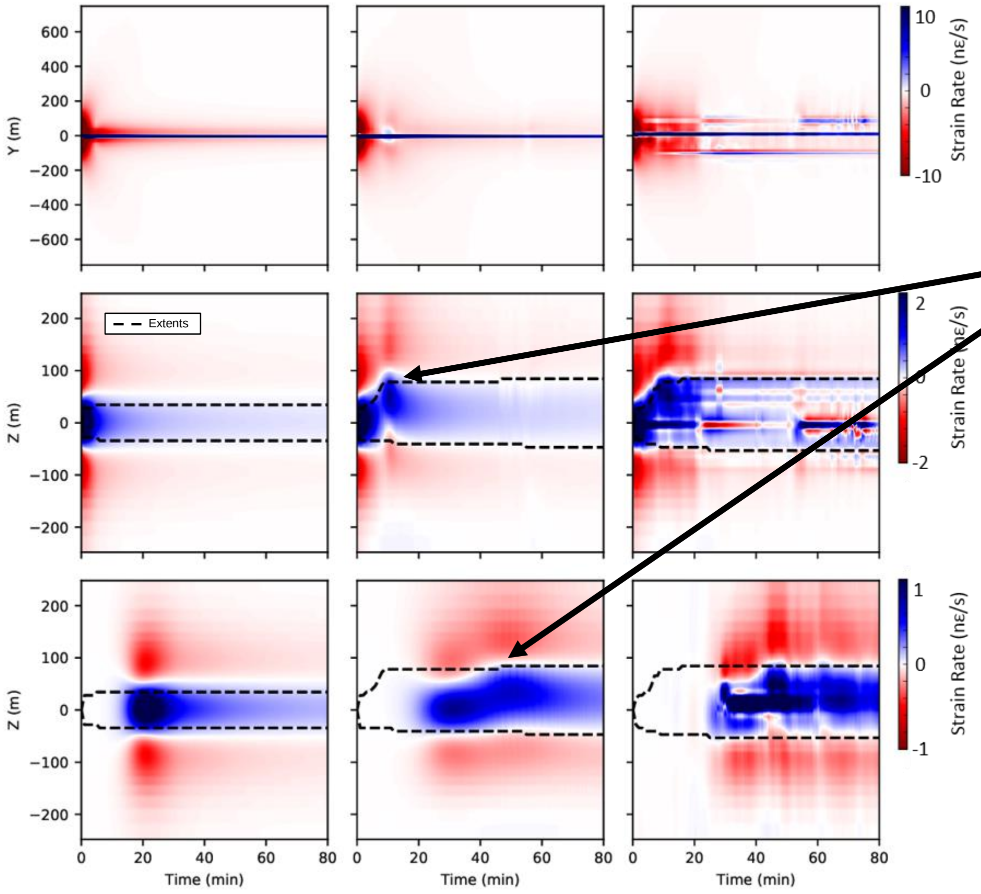
$F_{h,1}$

Vertical Offset Well (x = 0 m)

$F_{v,1}$

Vertical Offset Well (x = 380 m)

$F_{v,2}$



Model I

Model II

Model III

Base Model

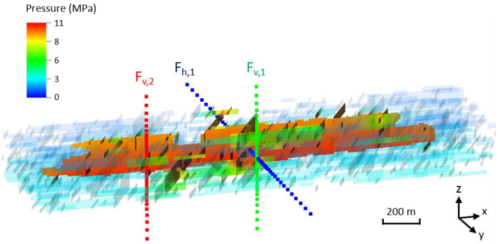
+ Stress Barriers

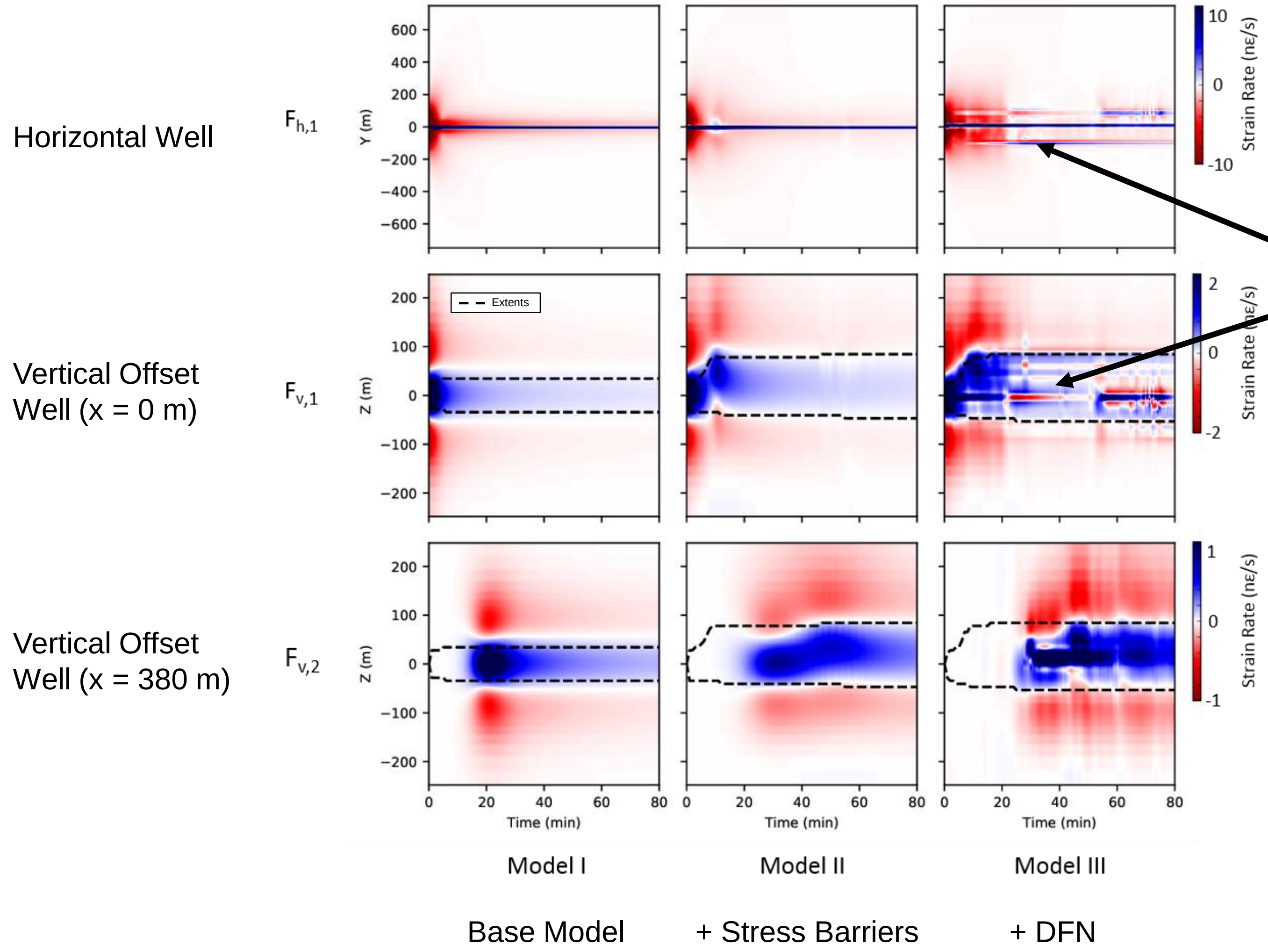
+ DFN

When a fracture breaks through a stress barrier near a fiber, it results in this characteristic bend shape

Extension Compression

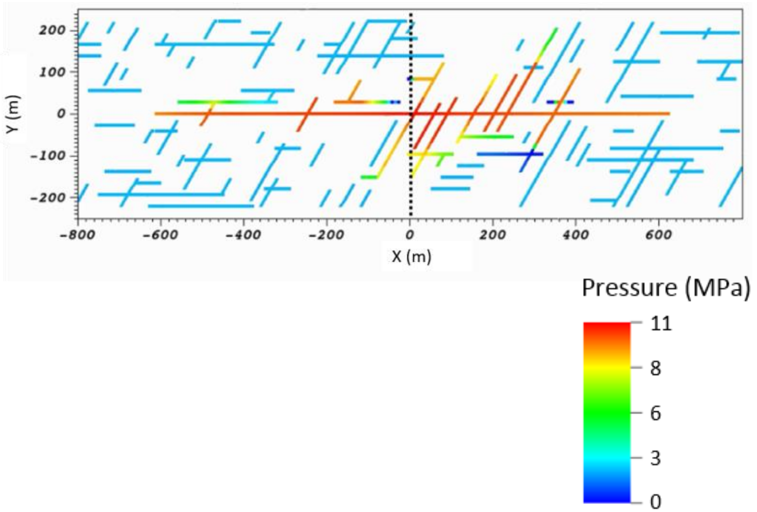
Geological Model Sensitivity – DAS Results





The presence of a DFN introduces significant complexity into the DAS response

Model III slice at z = 0 m:



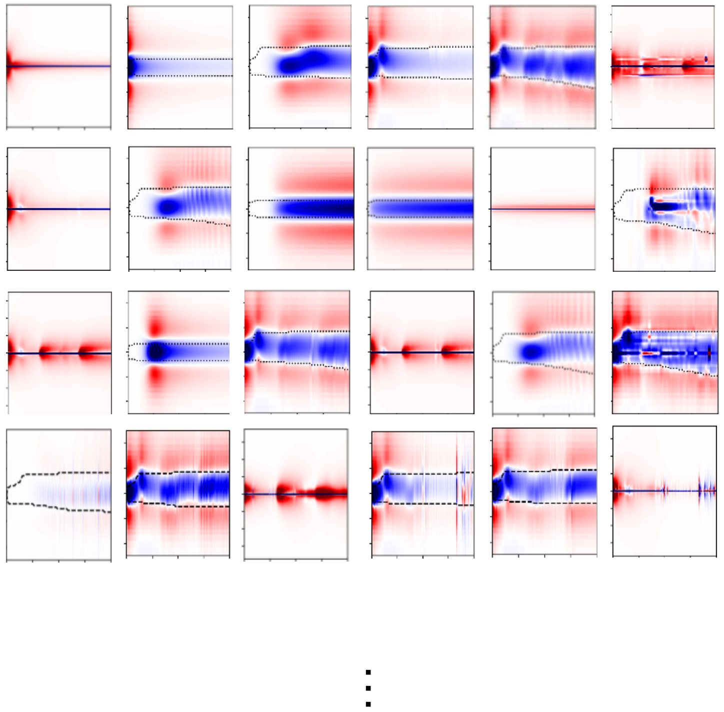
Extension Compression

Geological Model Sensitivity – Conclusions

- Low frequency DAS measurements may be used to constrain fracture geometry
- Synthetic DAS measurements may be used to design/optimize field deployments
- Simultaneous measurements in horizontal (common) and vertical offset wells (less common) allows best resolution
- DAS measurements may also be a useful tool for monitoring the interaction of fractures with barriers

Future Applications – Machine Learning

- Current effort to design machine learning approaches (CNN) to interpret these data
- Use our approach to generate a labeled training dataset:
  - Length/height of generated fractures
  - Location/timing of triggered microseismic events
  - Interaction with fracture barriers
  - Proppant and Multiphase related phenomena



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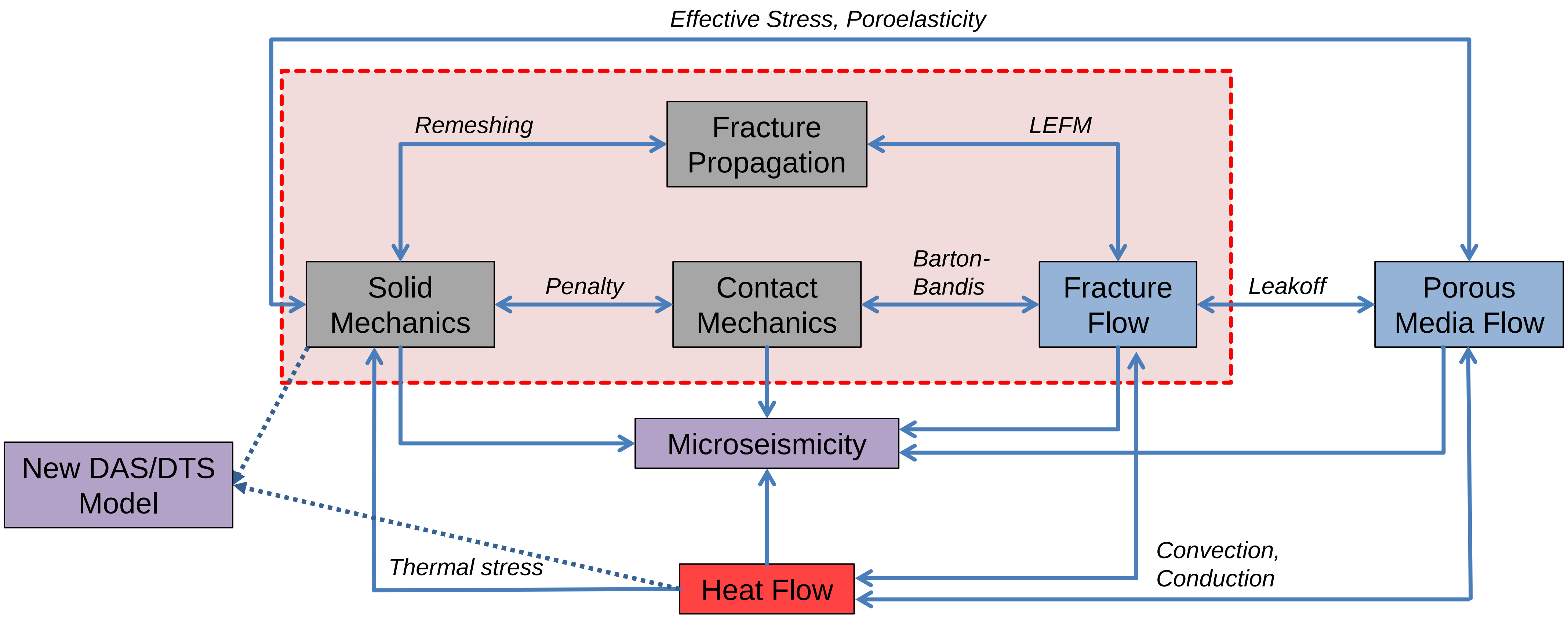
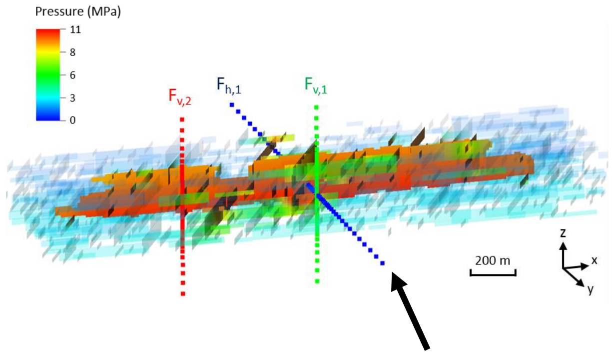
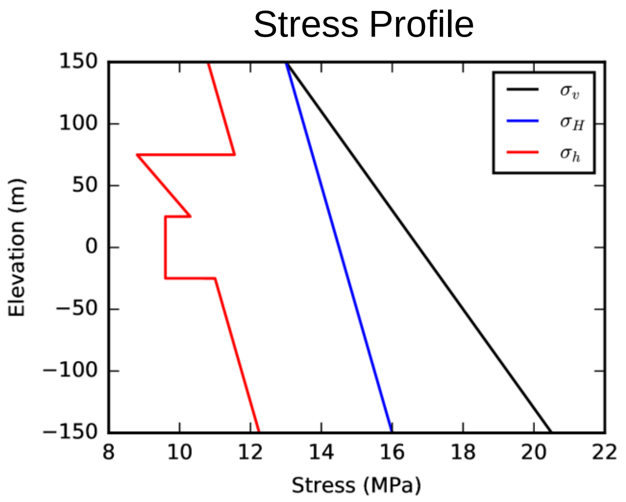
GEOS THM Coupling Diagram



Proppant Placement Sensitivity – Design

- Begin with Model II (stress barriers) as a reference
  - Incorporate a more realistic pumping schedule into the design
  - **Modify the fluid leakoff** rate into the surrounding formation
  - Track Changes in the DAS measured along the horizontal fiber F_{H1}
  - Compare to distribution of proppant in the generated fracture





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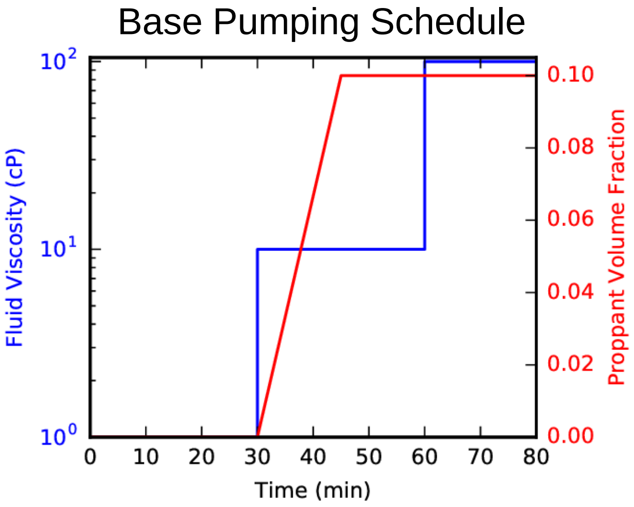
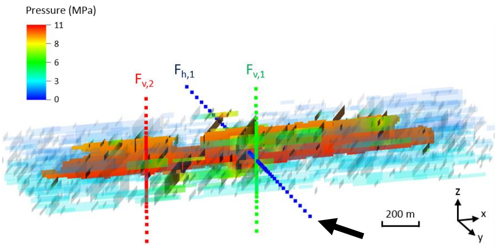
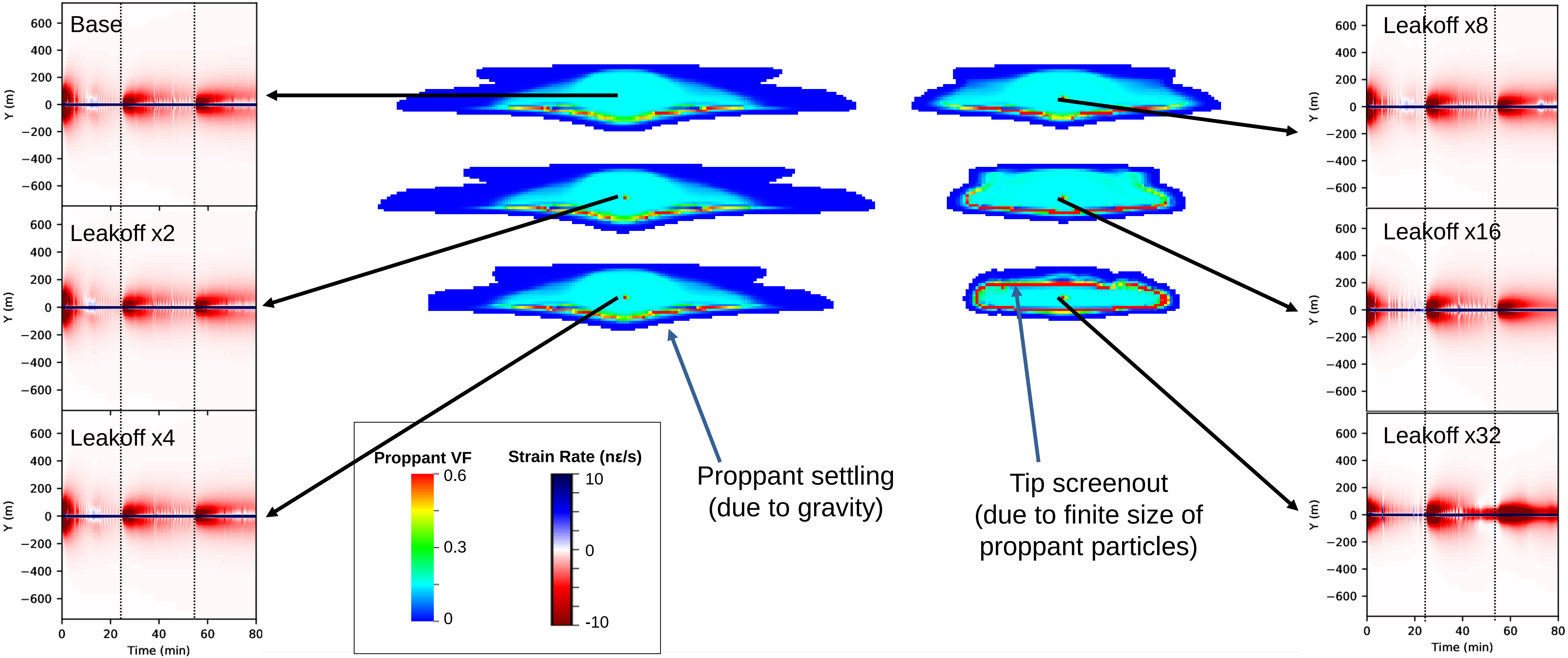


+ ***Leakoff Sensitivity***

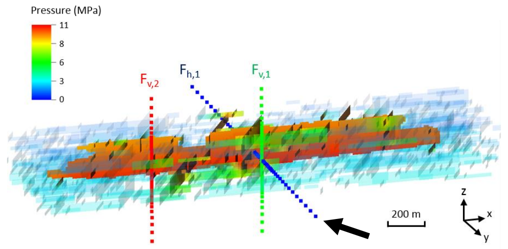
Proppant Placement Sensitivity – Results

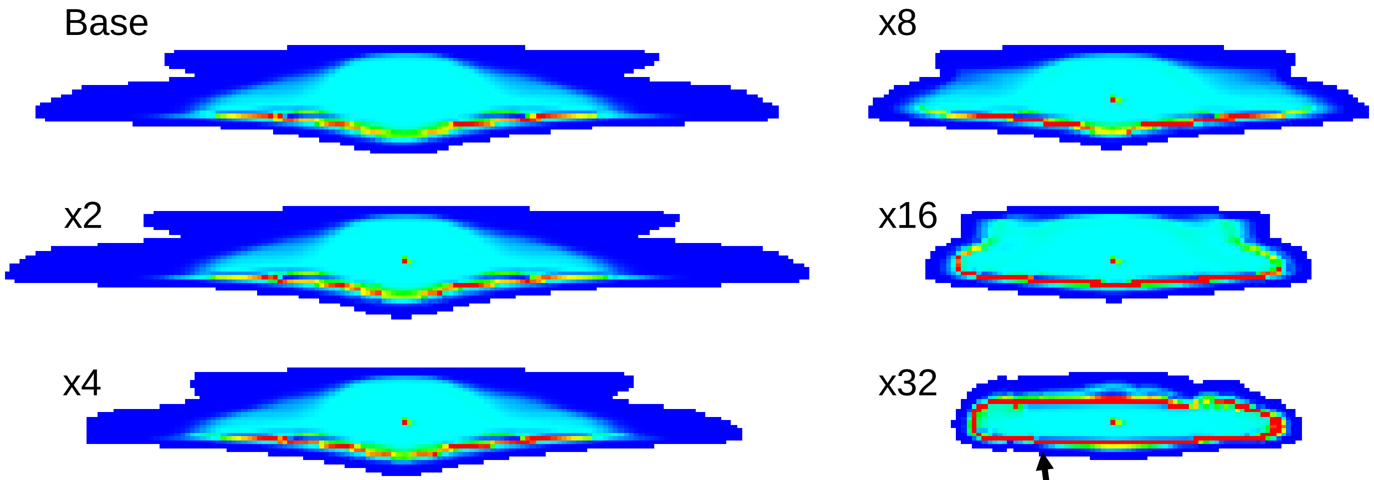


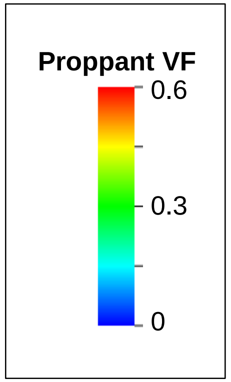


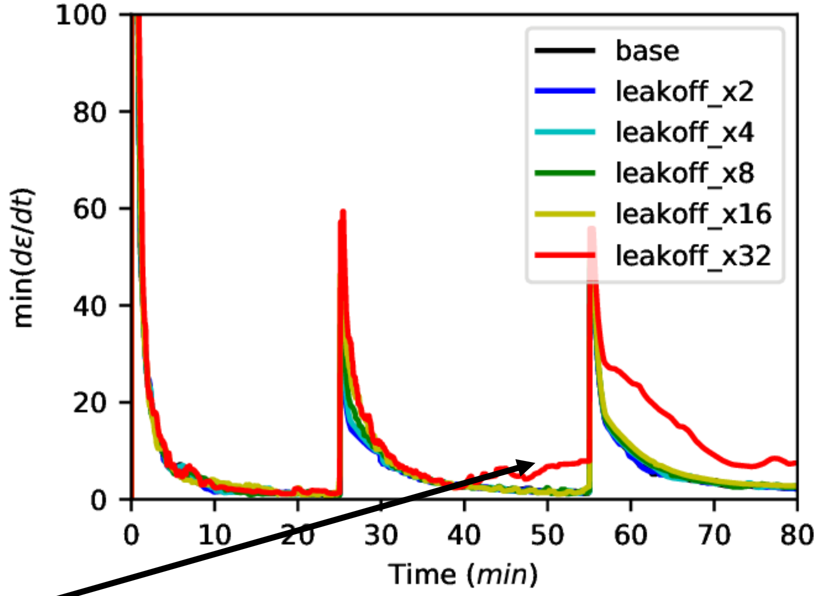
Extension Compression

Proppant Placement Sensitivity – Results









Tip screenout tends to appear as a deviation from the characteristic exponential steps. Otherwise, differences in proppant distribution are difficult to discern from these particular data